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Agricultural Memorandum No. 951

Weather and Spray Drift Part IV. Estimating spray drift using a random-walk model of evaporating drops: the model and some preliminary results

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SUMMARY

A random-walk turbulence model of atmospheric diffusion which gives good results in daytime conditions has been modified and applied to the simulation of the diffusion of evaporating, sedimenting spray drops. Drop size, wind speed, rate of evaporation, height of release, and whether or not the drops are collected with 100% efficiency by the underlying surface are factors which are demonstrated to interact strongly in their control of drop drift and deposition. The surface deposits at more than a few tens of metres from the source are always found to be increased by increasing wind speed, increasing height of release and increasing evaporation. Reducing the collection efficiency of the surface for the smaller drops leads as expected to reduced deposits at distances of a few tens of metres: however the consequent increase in numbers of drops remaining, particularly at larger distances, may eventually compensate for the partial reflection of drops at the surface, leading in some cases to deposits at larger distances which are at least as large as in cases where drops are not reflected at the surface.

1. Introduction

Numerous processes contribute to the movement of spray drops and the subsequent deposit of some of them outside their intended target area. Most important are (a) the size spectrum of the emitted drops, (b) the height distribution of each drop size fraction when the drops have deccelerated from their initially high ejection speeds to speeds where their subsequent trajectories are determined solely by settling velocity and atmospheric flows, (c) the wind speed and atmospheric turbulence, (d) rate of evaporation of the drifting drops, and (e) the collection efficiency of the underlying surface for the range of drops sizes involved. Some of these factors may interact: for example (b) (and possibly (a)) are linked to wind speed ((c)). These interactions usually prevent the use of results from limited numbers of field measurements of drift in deriving reliable general expressions for estimating drift.

An inherantly more satisfactory method ofestimating the magnitude of drift (and which is also much less expensive than comprehensive field experiments) is to construct physical models of the various processes contributing to drift, and then to verify that the models are able to produce results in fair agreement with those from a limited number of field experiments. The models' physical basis then allows their use in estimating drift over a wide range of meteorological conditions.

A simple model of spray drift (Bache and Sayer 1975) was used by Thompson (1981) to estimate drift deposits downwind from areas sprayed with non-volatile drops, but the approach is not suited to those cases in which the effects of drop evaporation are important. There is, however, a type of model which appears to be well-matched to applications involving diffusing, sedimenting, evaporating drops. This is the random-walk model which determines the drift deposits by simulating the trajectories of a large number of individual drops. Such an approach has been used successfully to simulate the dispersion of releases of neutrally-buoyant particles (eg Hall, 1975;

Ley, 1982) and may be readily adapted to cope with the effects of finite drop size and evaporation. The remainder of this memorandum is a description of this kind of model used in this application.

2. Random-walk modelling of spray drift

2.1 General considerations

The random-walk model assumes that the trajectories of individual drops, away from the immediate influence of the spraying system, can be represented by a connected series of discrete displacements determined in part by a random selection from appropriate Gaussion distributions of turbulent velocity. The broad details of simple random-walk models suitable for representing the effects of atmospheric turbulence have been described by Hall (1975). Considering for the moment the vertical component of drop motion (the treatment is readily extended to motion in three dimensions) Hall showed that the most satisfactory representation employed a Markov assumption in which the velocity w_{i+1} at any time step $i+1$ in the simulation is related to the velocity at the previous time step but with the addition of a random component and the fall speed of the drop v_s

$$w_{i+1} = \alpha w_i + \sigma_w (1-\alpha^2)^{1/2} \eta_{i+1} - v_{s_{i+1}} + \alpha v_{s_i} \qquad (1)$$

α is related to the Lagrangian scale of turbulence τ_L and the length of time step Δt : provided $\Delta t \ll \tau_L$, and with a number of lesser assumptions it may be shown that

$$\alpha = \exp(-\Delta t/\tau_L) \qquad (2)$$

σ_w is the standard deviation of the vertical velocity fluctuations, and η is a random variable with zero mean and standard deviation of unity. The treatment is valid only for drops with a fall speed small enough for them to respond adequately to the velocity fluctuations in the surrounding air; according to Smith (1959) this will be the case for fall speeds less than $2 ms^{-1}$, corresponding to water-based drops less than about $450\,\mu$ diameter.

In the case of horizontal motion, it is the alongwind component which is of most importance in the context of spray drift: crosswind diffusion is only of minor interest when the sprayed area has a crosswind width of several hundred metres. The random-walk representation of alongwind velocity u_{i+1} at time step $i+1$ is

$$u_{i+1} = \alpha u_i + \overline{U}(z_{i+1})(1-\alpha) + \sigma_u (1-\alpha^2)^{1/2} \beta' \qquad (3)$$

Here $\overline{U}(z_{i+1})$ is the mean wind speed at the height of the drop and β' is a random component which includes the effects of both turbulent fluctuations of horizontal velocity, and a correlation between vertical and alongwind turbulent fluctuations (Ley 1982):

$$\beta' = \frac{r}{2} \eta_{i+1} + (1 - \frac{5}{4} r^2)^{1/2} \varepsilon_{i+1} \qquad (4)$$

where

$r = u_*^2 / \sigma_u \sigma_w$ (the normalised velocity covariance)

ε_{i+1} = a random number from the same distribution as η_{i+1}

The position after n time steps of a drop released in the (x,z) plane at an origin $(0,Z)$ is then

$$(x,z) = \left(\sum_1^n u_i \Delta t_i , Z + \sum_1^n w_i \Delta t_i \right) \tag{5}$$

2.2 Model details

2.2.1 Drop fall speeds

The spray drops are assumed to contain an active chemical with specific gravity y, with water as the dilutant. The specific gravity S of the drops is then given by

$$S = 1 + f(y-1) \tag{6}$$

where f is the fractional concentration of chemical in the drop.

Mason (1971) gives a tabulation of the fall speed of water drops against their diameter d_μ (in microns), and fitting a simple polynomial leads to

$$\left.\begin{aligned} v_{s_w} &= 4.47 \times 10^{-3} d_\mu - 0.191 && d_\mu > 100\mu \\ v_{s_w} &= 3.2 \times 10^{-5} d_\mu^2 - 6.4 \times 10^{-8} d_\mu^3 && d_\mu < 100\mu \end{aligned}\right\} \tag{7}$$

The drops will contain around 1% chemical on release, if spraying is by a conventional hydraulic system, and so their settling speeds will be close to those given by eq (7) if no evaporation takes place. When evaporation occurs the drop density changes, and if all the water evaporates the final diameter will be around one fifth of the original. Drops with an initial size greater than about 200μ rarely contribute to drift, so the largest drift drops composed of chemical alone following complete evaporation of water are unlikely to exceed about 40μ diameter. In these circumstances the drops with specific gravities significantly different from unity will have diameters for which Stokes Law is applicable, and so it will be an adequate approximation to write

$$v_s = S v_{s_w} \tag{8}$$

2.2.2 Drop evaporation

A simple treatment of drop evaporation outlined by Goering et al (1972) and Williamson and Threadgill (1974), based on the treatment by Ranz and Marshall (1952) is well suited to applications with random-walk models. It provides a relation for rate of decrease of diameter d of a drop with time as

$$\frac{d}{dt} d = -2 \frac{M_v}{M_a} \cdot \frac{D_v}{d} \cdot \frac{\rho_a}{\rho_\ell} \cdot \frac{\Delta p}{P_a} \left(2 + 0.55 (Sc)^{1/3} (Re)^{1/2}\right) \tag{9}$$

where M_v and M_a are the molecular weights of the diffusing vapour and air, D_v the diffusion coefficient of the vapour in air, ρ_a and ρ_ℓ the air density and density of the evaporating liquid, Δp the vapour pressure difference (saturation vapour pressure at drop surface-vapour pressure in surrounding air), P_a the partial pressure of air and Sc and Re the Schmidt and Reynolds number.

The treatment is kept as simple as possible by assuming that mass transfer from the drops takes place as if they are pure water, until only the active ingredient remains. On this assumption the temperature of the drops is close to the wet-bulb temperature of the air (Ranz and Marshall, 1952), so that when this temperature is measured with an aspirated psychrometer

$$\Delta p = 67 \times \text{wet-bulb despression in deg C} \quad \text{(Pascals)}$$
$$= 0.67 \times \text{wet-bulb depression in deg C} \quad \text{(mb)} \qquad (10)$$

Difficulties arise when the evaporation process differs from the simple two-phase system described here, for example if surface-active material from the spray chemical is present at the drop surface rather than pure dilutant. However, it appears that the simple treatment does in many cases represent adequately the evaporation of water-based chemical sprays (Wanner, 1980).

Equation (9) may be simplified by selecting values for its variables appropriate to water-based sprays. Thus

$M_v = 18$

$M_a = 29$

$D_v = 2.34 \times 10^{-5}\ m^2 s^{-1}$ (at 15 deg C)

$\rho_a = 1.23\ Kg\ m^{-3}$

$\rho_\ell = 1000\ Kg\ m^{-3}$

$P_a = 10^5$ Pascals

$$Re = \frac{v_s d}{\nu}$$

$\nu = 1.46 \times 10^{-5}\ m^2 s^{-1}$ (at 15 deg C)

$$Sc = \frac{\nu}{D_v} = 0.62$$

Then,

$$\frac{d}{dt} d = \frac{-3.58 \Delta p \times 10^{-13}}{d} (2 + 124 (v_s d)^{\frac{1}{2}}) \qquad (11)$$

Writing this equation in terms of drop diameter expressed in microns (d_μ) leads to

$$\frac{d}{dt} d_\mu = \frac{-0.358 \Delta p}{d_\mu} (2 + 0.124 (v_s d_\mu)^{\frac{1}{2}}) \qquad (12)$$

2.2.3 Representation of boundary layer variables in the random-walk equations

The necessary relations are derived from similarity theory and diabatic flux-profile relationships (Appendix 1).

2.2.4 Model time step

A basic time step of 1s is used, but this is reduced when drops approach the surface. Eq (A.12) shows that the Lagrangian time scale is roughly proportional to height above the zero plane, and so in order to satisfy approximately the conditions under which eq (2) is applicable, the time scale is reduced to 0.2s ($1m < z-h < 0.5m$) and to 0.1s for $z-h < 0.5m$.

2.2.5 The lower boundary conditions

Drops which penetrate the crop canopy may re-emerge if caught in a strong-enough updraught before impaction on foliage. The chance of re-emergence is reduced as the distance below the canopy top increases. Few of the larger drops are likely to escape from the canopy once they penetrate its top because of their large settling velocities and high chance of impaction on foliage. An acceptable boundary condition in their case would be the assumption that all drops are captured by the canopy as soon as z becomes less than h. The opposite extreme is represented by very small drops with negligible settling velocities, and insignificant impaction efficiency onto foliage. After entry into the canopy, the majority of these drops will fail to be retained there.

There are some experimental data to support these speculations. Hall (1974) in experiments on the deposition of drops on grassland found from a comparison of observed and calculated values of drift that the reflection coefficient of the grass-covered surface increased as v_s/u_* decreased. Lawson and UK (1979) measured the deposition of aerial sprays on wheat 0.6m high, and on bare soil with crosswind plough furrows about 0.25m deep; using the model of Bache and Sayer (1975) they demonstrated that over wheat the collection efficiency of the surface was close to 1 for drops larger than about 50μ, but in the case of bare soil, efficiencies appeared to be less than 1 for sizes up to at least 100μ.

An outline of a theoretical approach to the estimation of surface collection efficiency has been given by Bache (1979a, b) but is not suitable for incorporation in the present model. Two different approaches to the problem of the lower boundary have been adopted here. In the first the trapping surface for the drops is assumed to be at $z=h$; the collection coefficient is either equal to 1 for all drop sizes, or decreases from 1 for 100μ drops to 0.05 for 10μ drops. A more realistic representation of likely variation of collection efficiency with drop size would include a dependence on wind speed and on v_s/u_*; however a simple linear relation is used, essentially to test the significance of varying the collection efficiency in the model, since experimental and theoretical evidence is inadequate at present to provide a definitive relation. The second scheme for the boundary condition sets the trapping surface at the zero-plane displacement height, with the assumptions about collection efficiency the same as before. In this latter scheme a method other than that represented by eq (A.12) is required to

describe the Lagrangian time scale within the upper part of the canopy (eq (A.12) is probably not valid close to (above) the canopy either (eg Garratt, 1980) but errors introduced by its application there are unlikely to be large). Within the canopy the eddy diffusion coefficient $K(z)$, and presumably the Lagrangian time scale, decreases with increasing distance below the canopy top; the decline in K follows roughly the form (eg Denmead, 1976).

$$K(z) = K(h) \exp(-2.5(1-z/h)) \qquad (13)$$

The corresponding behaviour of T_L is not known, and in view of the general uncertainty regarding the magnitude of the various micrometeorological quantities in the vicinity of the canopy top the simplifying assumption is made that T_L is constant within the upper canopy ($0.63h < z < h$), and is given by eq (A.12) evaluated at $z = h$.

3. Results

The five main influences on the drift of spray drops are

i. Effective height of release (ie the height at which, after ejection from the spraying device, the drops have deccelerated to a speed at which their subsequent motion is determined solely by their settling velocity and atmospheric flows).

ii. Drop size.

iii. Wind speed.

iv. Atmospheric stability.

v. Rate of drop evaporation.

Simulations of drop trajectories were carried out for the following variable values:

Wind speed at 10m	1, 2, 10 m/s
Crop height	0.2, 1.0 m
Effective release height above crop	0.2, 0.5, 1.0 m
Initial drop sizes	50, 100, 150, 200
Relative humidity	100%, 50% at 20 deg C
Weather	Overcast, (near neutral stability), or bright sunshine (unstable).

Trajectories were calculated up to 1 km from the release point; it was necessary to follow the trajectories of up to 10,000 individual drops in each of the cases defined by combination of the variable values above in order to reduce the statistical variability of the calculated deposits at the longer distance to a level where reliable smooth curves of deposit density against distance could be drawn. However, it was necessary first to test the sensitivity of the model to the boundary assumptions discussed in § 2.2.5.

3.1 The influence of the lower boundary condition

The effects of the different boundary conditions are negligible for the large drops, for the reasons given in § 2.5.5. Unfortunately it is not possible to define a particular drop size below which the boundary assumption will affect significantly the calculated drop deposit densities, because of the interacting effects of release height, drop evaporation and atmospheric turbulence.

Hydraulic sprayers typically eject the spray liquid downwards at around 20ms^{-1}. The sheet of liquid entrains air as it moves downwards and breaks up, and this results in stopping distances for the spray drops larger than those for drops ejected singly into still air. Even in the latter case the stopping distance for 150 μ drops is 0.5m, and for 200 μ drops is 0.75m; most sprayers usually operate at around 1m above the crop and so the effective release height of 150 μ drops will not usually exceed around 0.5m above the crop. In these circumstances it is only in stronger winds ($\sim$10ms^{-1} at 10m height) that the boundary assumption has a significant effect on the calculated deposits of 150 μ drops. In the case of 200 μ drops the calculations showed that even for effective release heights as high as 1m above the underlying crop, and in wind speeds up to 10ms^{-1}, it may be assumed that the deposits are little influenced by the boundary assumption.

It is for smaller drop sizes that the exact form of the lower boundary condition usually becomes important for conventional spraying systems. In their case the total volume of spray below a given drop size increases sharply with increasing drop size. It may be assumed for these sprayers that a significant fraction (of the order of 10%) of the total volume is emitted in the form of drops less that 100 μ in diameter. Drops of these sizes evaporate quickly in suitable conditions and therefore become liable to drift. It is convenient then to discuss the boundary condition in the context of evaporating drop initially 100 μ in diameter.

Table 1 shows some results obtained using the following boundary conditions:

either (a) complete absorption of the drops when they fall below the top of the canopy (height h)

or (b) complete absorption of the drops when they fall to height $0.63h$

or (c) partial absorption of the drops at either (1) h or (2) $0.63h$; the absorption coefficient (β) is assumed to decrease linearly from 1 (100 μ) to 0.1 (20 μ).

The drops are assumed to contain 1% by volume of pesticide on release, and be water-based, so that their final diameter following complete evaporation of water is $(100)^{\frac{1}{3}} \simeq 22\mu$: a specific gravity of 1 is assumed for the chemical. In cases C1 and C2 the drops are assumed reflected at the surfaces, but with their vertical velocities at the next time step calculated exactly as before, using eq (1). A third case (C3) is also considered in which, after reflection, the drop is postulated to have no vertical velocity; its velocity at the next time step includes therefore only the random component and fall speed in eq (1). The results in the Table are expressed as average numbers of drops deposited per square metre at different distances downwind from a crosswind line source emitting 10000 drops per metre of line. The drops are released at an effective height of 0.5m above a crop 0.2m high. Conditions are either neutral, or unstable (L = -20m), with wind speed of 5ms^{-1} at 10m height. The relative humidity is assumed to be 50% (air temperature 20 deg C). The results (and others, not shown here, for different heights and wind speeds) generally indicates only small differences between deposit densities calculated for absorption heights of h or $0.63h$: differences between cases C1 and C3 are also small usually. However, the effect of decreasing the absorption coefficient β when the drop size decreases are not always insignificant and this point will be enlarged on shortly. In the remainder of this memorandum it will be assumed that the absorption surface for the drop is located at the top of the crop, and in those cases where droplet reflection occurs, the velocity of the drop immediately after reflection follows from eq (1) (case C1).

Table 1 Deposit densities for evaporating drops of 100 μ initial diameter

Atmospheric stability	Downwind distance (m)	Deposit density (drops/m^2)				
		a	b	c1	c2	c3
Neutral	10	280	280	280	280	260
	50	7	7	4.2	4.0	3.6
	100	1.8	1.8	1.3	1.6	1.3
	500	0.17	0.18	0.13	0.24	0.20
Unstable	10	260	260	250	290	260
	50	7	8	5.5	7	5.5
	100	2.2	2.8	1.7	1.9	1.5
	500	0.25	0.26	0.24	0.25	0.23

3.2 General results

Several hundred sets of results have been obtained: only a small proportion of them will be discussed. Of most interest are the results for smaller drops (100 μ and less) since significant drift for drops of 150 μ size or larger occurs only in stronger winds - force 4 and above - or with effective release heights of 1m or more in lighter winds, corresponding to boom heights of at least 1.5m above the crop surface.

Table 2 shows the effects of release height and stmospheric stability on deposit densities of non-evaporating 100 μ drops, which are assumed to be completely absorbed when they first penetrate the crop canopy. The results are expressed as average numbers deposited per square metre at different distance downwind from a crosswind line source emitting 10,000 drops per metre of line. The deposits are seen to fall off rapidly with increasing distance, becoming roughly proportional to x^{-2} at large distances.

Table 2 Deposit densities for non-evaporating drops of 100 μ diameter (wind speed = 5m/s)

Effective release height(m)	Atmospheric stability	Deposit densities (drops/m^2) at: 10m	50m	100m	500m	Drops still airborne at 500m (%)
0.2	Neutral	80	1.3	0.23	0.005	< 0.1
	Unstable	100	2.9	0.6	0.02	0.2
0.5	Neutral	260	4.4	0.9	0.02	0.1
	Unstable	280	9	2.0	0.09	0.5
1.0	Neutral	500	12	2.0	0.03	0.2
	Unstable	420	22	3.0	0.20	1.4

Increasing the release height increases the deposit in roughly the same proportion. Both these results are consistent with those from sedimenting plume models of drop dispersion such as that of Bache and Sayer (1975). Substantially larger deposits are found at larger distances in cases where the atmosphere is unstable, but even here the number of drops remaining airborne at 500m is very small.

The corresponding results for evaporating drops are given in Table 3. Here those drops remaining airborne for more than about 20s will lose all their water and decrease in size to about 20μ. Such small drops are unlikely to be collected by the crop without partial reflection: results in the Table are given for β decreasing from 1.0 for 100μ drops to 0.1 for 20μ drops, and also $\beta = 1$ for all sizes.

Table 3 Deposit densities for evaporating drops @ 100μ initial diameter (wind speed = 5m/s)

Release height(m)	Atmospheric stability	Deposit density (drops/m^2) at: 10m	50m	100m	500m	Drops still airborne at 500m (%)
0.2	Neutral[a]	80	1.8	0.6	0.04	1.0
	Neutral[b]	80	1.4	0.5	0.06	1.9
	Unstable[a]	95	3.0	0.9	0.08	2.0
	Unstable[b]	120	2.1	0.7	0.07	3.0
0.5	Neutral[a]	280	7	1.8	0.17	3.1
	Neutral[b]	280	4.2	1.3	0.10	5.3
	Unstable[a]	260	7	2.2	0.25	5.4
	Unstable[b]	250	5	1.7	0.24	8.4
1.0	Neutral[a]	400	16	4.6	0.40	8.4
	Neutral[b]	400	9	3.7	0.45	13.0
	Unstable[a]	380	16	4.6	0.5	11.4
	Unstable[b]	370	9	3.8	0.6	17.5

a: $\beta = 1$ for all drop sizes

b: β decreasing from 1.0 (100μ drops) to 0.1 (20μ drops)

A comparison with the previous Table shows that the reduction in fall speed of the drops following evaporation produces a substantial increase in the numbers remaining airborne, and a several-fold increase in deposit densities at the larger distances. At shorter distances ($\lesssim$ 50m) such a comparison produces a less clear-cut outcome, demonstrating the complexity of the interacting effects of drop fall speed, release height, atmospheric stability and wind speed.

The results in Table 3 indicate an unexpectedly small effect on deposit densities when β for the smaller drops is decreased from 1.0 to close to zero. The final column of the Table shows that a consequence of partial reflection is a larger number of drops (about 50% more) still airborne at 500m. This increase in drop numbers would be completely inadequate to compensate for a small absorption coefficient ($\simeq 0.1$) if the additional (reflected) airborne drops were distributed in the vertical in the same way as the unreflected ones. However, when drops are reflected they are likely to remain close to the surface for some time (and possibly undergo further partial reflections) because of the small scale of atmospheric turbulence near the surface. The reflected drops therefore produce a substantial increase in the average numbers fairly close to the surface at any time, and in terms of deposit densities this appears largely to compensate for the small absorption coefficient. Some vertical profiles of airborne drops obtained by Lawson and Uk (1979) support this idea. Closer to the source the results in the Table, and those plotted in Figure 1, demonstrate that a small absorption coefficient for the small drops causes a significant reduction in the surface deposit. This is because at these distances few of the airborne drops have been reflected, so that drop numbers near the surface are similar, whether or not partial reflection is taking place.

Calculations for drops with 50 μ initial diameter show effects of release height and atmospheric stability on deposit densities which are similar to those for 100 μ drops. However, the small settling speed of 50 μ drops leads to greater drift, but also to a smaller increase in drift when the drops evaporate since in all but very light winds the typical vertical turbulent velocities of the air are significantly larger than drop settling speeds.

4. Conclusions

The random-walk model is a valuable aid in quantifying spray drift, not only because it can simulate the effects on drift of release height, atmospheric stability and the vertical wind profile, but also because it provides an accurate method of incorporating the effects of drop evaporation and partial reflection at the surface. Results from the particular model which has been described here have demonstrated the complexity of the interaction of the various factors which determine drift, underlining the difficulties of extrapolating the results from a limited number of field experiments in order to predict drift over a wide range of initial conditions.

One point of particular interest which has emerged from the calculations is that a large reduction in surface drop deposits caused by partial reflection of drops at the surface will only be observed at relatively short distances from the source: at longer distances increased numbers of drops remain airborne as a consequence of reflection, with most of the additional drops drifting along near the surface, and this tends to compensate for the reduced collection efficiency of the surface.

Any comments or suggestions on this paper should be referred to the authors.

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August 1982

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Appendix 1

Representation of boundary-layer variables in the random-walk equations

The surface over which the drops are released is assumed to be covered with vegetation of height h ($h<Z$): typical values for $Z-h$ will be 0.5-1m. The roughness length z_0 and displacement height d' of the vegetated surface are then (Monteith 1973)

$$z_0 \simeq 0.1h \tag{A.1}$$

$$d' \simeq 0.63h \tag{A.2}$$

The vertical gradient of the mean horizontal wind speed $\bar{U}(z)$ is (Dyer 1974)

$$\frac{\partial \bar{U}(z)}{\partial z} = \frac{u_*}{k(z-d')}\ \phi_m\left(\frac{z-d'}{L}\right) \tag{A.3}$$

where

k = von Karman's constant ($\simeq 0.4$)

u_* = friction velocity

L = Monin-Oboukhov length (<0 in the assumed daytime conditions)

and

$$\phi_m = \left(1-16\left(\frac{z-d'}{L}\right)\right)^{-1/4} \tag{A.4}$$

Substituting (A.4) into (A.3) and integrating gives

$$\bar{U}(z) = \frac{u_*}{k}\left[f(\zeta)-f(\zeta_0)\right] \tag{A.5}$$

where

$$\zeta = \frac{z-d'}{L}$$

$$\zeta_0 = \frac{z_0}{L}$$

and

$$f(\zeta) = 2\tan^{-1}\left\{(1-16\zeta)^{1/4}\right\} - \ln\left(\frac{1+(1-16\zeta)^{1/4}}{1-(1-16\zeta)^{1/4}}\right) \tag{A.6}$$

Panofsky et al (1977) suggest that

$$\sigma_w = 1.3u_*\left(1-3\left(\frac{z-d'}{L}\right)\right)^{1/3} \tag{A.7}$$

$$\sigma_u = 3u_* \tag{A.8}$$

The Lagrangian time scale is given approximately by (Ley 1981, 1982)

$$\tau_L = K_{mass}/\sigma_w^2 \tag{A.9}$$

where K_{mass} is vertical eddy diffusion coefficient for mass transfer. From similarity theory,

$$K_{mass} = ku_*(z-d')/\left(\phi_{mass}\left(\frac{z-d'}{L}\right)\right) \tag{A.10}$$

Also (Dyer, 1974)

$$\phi_{mass}\left(\frac{z-d'}{L}\right) = \left(1-16\left(\frac{z-d'}{L}\right)\right)^{-1/2} \tag{A.11}$$

Combining these last three equations leads to

$$\tau_L = \frac{ku_*(z-d')}{\sigma_w^2}\left(1-16\left(\frac{z-d'}{L}\right)\right)^{1/2} \tag{A.12}$$

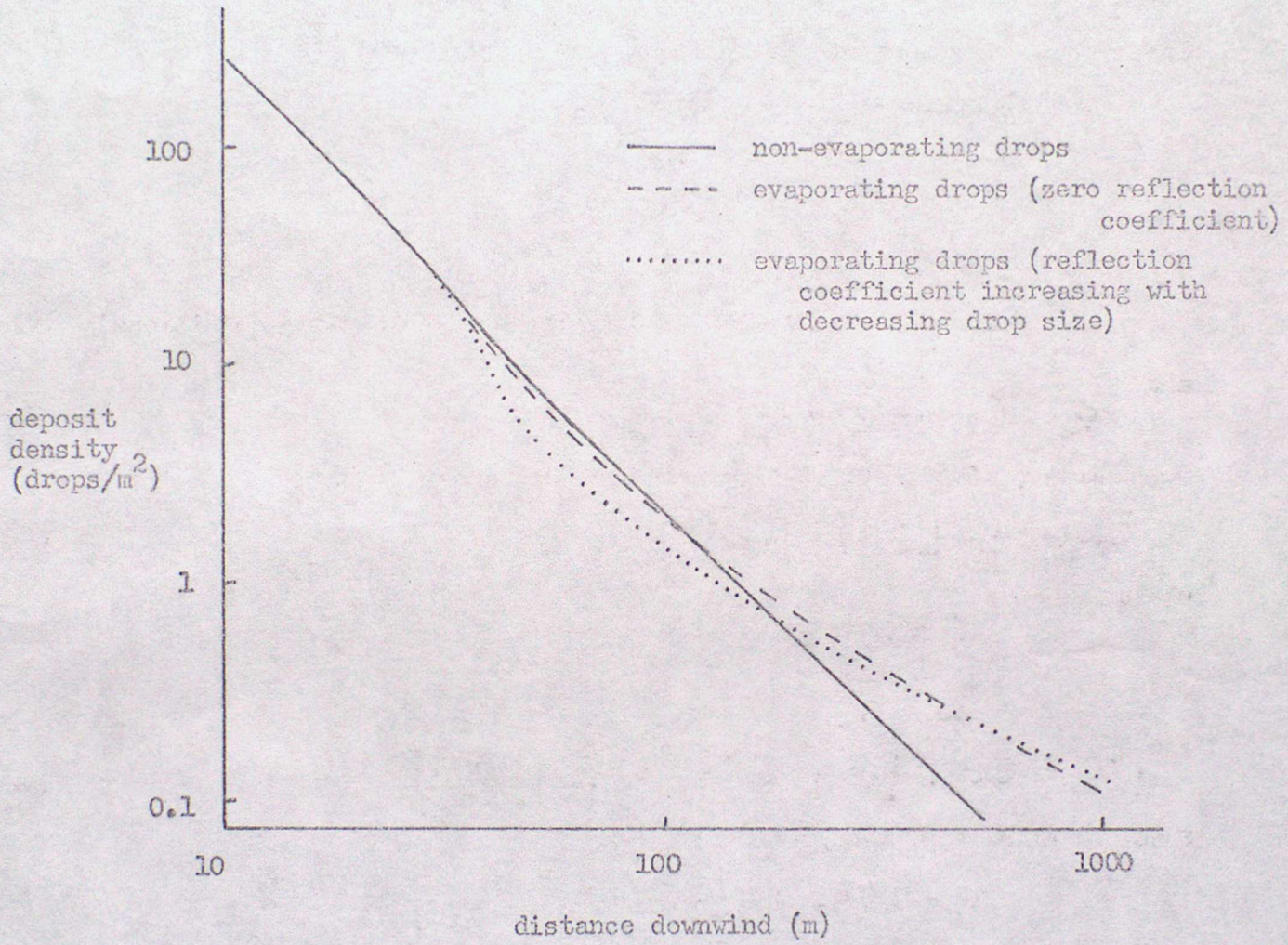

Figure 1 Deposit densities for evaporating and non-evaporating drops, 100 μ diameter initially, released 0.5m above a crop in unstable conditions, with wind speed at 10m height of 5 ms^{-1}